Nat. Hazards Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/nhess-2020-72-AC1, 2020

Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "What controls the coarse sediment yield to a Mediterranean delta The case of the Llobregat river (NE Iberian Peninsula)" *by* Juan P. Martín-Vide et al.

Juan P. Martín-Vide et al.

juan.pedro.martin@upc.edu

Received and published: 19 May 2020

ANSWER TO Review nhess-2020-72, Martín-Vide et al., by Carles Ibáñez

REVIEWER:Very interesting paper that, however, shows some important caveats that need to be solved before a decision of publication can be made. The paper needs a major change in the focus and the specific goals to sort out the weak points that contains right now. The starting point is the observed secular coastal retreat of the Llobregat Delta. This is an interesting new piece of information that gives value to the manuscript but at the same time shows the limitation of the approach taken. For me it was a surprise to see that the Delta was already retreating quickly by the end of

Printer-friendly version

Discussion paper

the XIX century and that the retreat kept going all over the time till nowadays. This is very interesting, but in my opinion the possible causes argued in the manuscript to explain it are not convincing. In terms of damming the authors mention two dams built in the last decades in the upper basin, while river channelization is also relatively recent and cannot be the main cause of such a dramatic coastal erosion. The main argued possible cause is reforestation, but again the process is not so widespread from the beginning of the observed retreat and the increase in forest cover along the study period is not so large to explain the most of the deficit in sand delivery to the delta. According to Table 2 forest shifted from a cover of 63% in 1956 to a cover of 70% in 2009 for the whole river basin, and this is the main period of afforestation, mostly driven by the abandonment of traditional farming and public policies during the last decades of the dictatorship regime. At the same time, data also shows that large floods (a major source of sand delivery to the coast) have apparently been occurring all along the study period (a more detailed analysis of the changes in river floods along time could help to understand what's going on).

AUTHORS:The reviewer is right. The land use change is now considered a minor factor. The role of the floods has deserved more consideration in the new text, by evaluation of the floods in the XX century, as well as in the XIX century.

REVIEWER: There must be other causes to explain the sediment deficit in the delta, and the main one that comes to me is the widespread construction of weirs in the Llobregat River and its main tributaries (such as the Cardener) for industrial production (mostly textile) and for hydropower, that was already important in the XIX century. This chain of small reservoirs certainly modified in a dramatic way the hydro-sedimentary dynamics of the Llobregat River and tributaries, and could mostly explain what happened in the Llobregat Delta in terms of erosion. Thus, the paper needs to investigate this point as much as possible, both in terms of data (on the evolution of damming in the basin), mechanisms (how this damming modifies the sedimentary dynamics) and potential effects on sand delivery to the coast.

AUTHORS: The reviewer is right. Thanks for the suggestion, which has produced a strong change in the discussion section of the new text. It has been proved the paramount role of these weirs (small dams), standing in the middle reaches of the river, on the sediment dynamics. Parts of the new discussion are:

However, despite all the analysis shown so far, the influence of the modern river channelization on the delta evolution is overrun by a much larger long-term trend of the Llobregat delta, which is irreversible as we will see. In fact, the contribution of the channelization to the total retreat in the period of analysis, 1946-1981, has been evaluated above as just 18-20%. The retreating trend was clear in fig.2, updated several times to add new historical data while the effect of channelization was being analyzed. The most advanced delta coastline must have occurred around the turn of the XX century, between the 1891 and 1907 coastlines. The question is why the delta was prograding in the XIX century, at least since 1862, but retreating continuously during the XX century. Is there any explanation for the trend shift around 1900?

Case-studies of rivers in southeastern France (Liébault and Piegay, 2002) suggest that a reforestation policy in the last 150 years, applied to Catalan basins as in the French examples, may be influential in narrowing river channels and so, indirectly, in the retreat of deltas. However, the decrease of sediment sources (less agriculture and more forest) seems very modest in this case (table 2), even more modest in the context of recent research that proves a weak signature of deforestation on delta size, because fine sediments contribute little to delta progradation (Ibáñez et al, 2019).

A second reason stems from a particular hydrological regime in the XIX century. Following documentary research, the period 1830-1870 was marked by a high frequency of floods in the Llobregat and other rivers of Mediterranean Catalonia (Llasat et al, 2005; Barriendos et al, 2019). The most severe floods occurred in 1837, 1842, 1853 and 1866 (Barriendos and Rodrigo, 2006). The XX century has been less active: 6 catastrophic events in the XIX versus only 1 in the XX (Llasat et al, 2005). A natural origin of this anomaly is accepted in the literature on the grounds of its temporary course and the corresponding climatic oscillations between several European regions. It can be assumed that these flood pulses produced an advance of the delta.

A third reason is the development of garment factories on the banks of the Llobregat river to profit from waterpower, in the XIX century (Alayo, 2017). This can be asserted for 91 factories in the middle reaches of the river (see “small dams” sign in fig.1), consisting of a diversion dam with average height of 4,2 m $\pm$ 2,9 m (standard deviation). Some 62% of them were built between 1850 and 1900 and most are still in operation as small hydro plants. More specifically, fig.1 is the graph of the cumulated height (m) versus the date of the insertion (calendar years) of small dams in the river. Following the progressive dam insertion, the span in height that keeps free for flow of water and sediment in the river profile is reduced accordingly. Recalling that the bed load carrying capacity is a monotonically increasing function of this free span, fig.1 also serves as a surrogate of the reduction in carrying capacity over the years. These 91 small dams date from 1816 till 1963 and stand from 4 to 100 km away from the upper border of the lower Llobregat reach. The delayed effect of the farthest dams, and the quick effect of the closest, in the way to reach this border is taken into account by a disturbance velocity. The graphs for velocities 2 km/year, 1 km/year and 0.5 km/year are plotted in fig.8. Note that the latter has been used in the sediment routing through the five reaches of the lower Llobregat above. These graphs express the pace of the decrease in sediment supply at this border due to the space and time dispersion of the factories.

Here stands fig.1, Caption: Cumulative height H (m) versus calendar date for the installation of factories in the middle reaches of the river (data in Alayo, 2017), and its effects at the upper border of the lower Llobregat, under three assumptions of disturbance velocity.

Two points are worth of discussion in fig.1: i) the hydrological anomaly of 1830-1870 finds the middle reaches of the river before the heyday of the garment factory building; therefore, the severe floods of this period must have brought large amounts of sediment to the lower Llobregat, and ii) the increasing effect of factory building on the sediment supply to reach 1 spreads throughout the XIX and XX centuries, including the period 1946-1981 of our main analysis, and even beyond; the turn of the century (1900) may be spotted as the fastest increasing supply cut in case of a 2 km/yr disturbance (or the incipient cut for a 0.5 km/yr disturbance) in order to explain the shift from progradation to retreat in the delta. Obviously, the recovery of free span in height in the middle river by removing small dams would be effective to increase the sediment delivery to the delta, in the long term (Ibisate et al., 2016).

In the event of a more active Llobregat in the middle years of the XIX century, and mostly free of factories in the middle reaches, the alluvial channel in the lower river should have been much wider at that time. Very fortunately, two plans of the lower Llobregat at reach 3, dated 1846 and 1854 just in the years of the hydrological anomaly, do exist in the National Archives to check our hypothesis. They can be scaled by means of landmarks in towns C and D and specially thanks to the historical bridge close to D that failed in 1971. Moreover, fig.2 is a photograph dated 1866-1867 of this bridge, a very telling picture of the largest alluvial width known and the plenty of sand and gravel there at that time, completely lost today. The average widths within reach 3 from the two plans are 272 m (both 1846 and 1854), with maxima of 447 m (1846) and 579 m (1854) and minima of 155 m (1846) and 123 m (1854). Compare this with an average width of 150 m for reach 3 in 1946 (table 4). This result closes the explanation of the delta retreat in fig.2. The heyday of the sediment yield to the delta was the middle of the XIX century. In 1900 things had started to change.

Here stands fig.2. Caption: Bridge close to town D, shot by well-known French photographer Jean Laurent probably in 1866-1867. The only bridge in lower Llobregat at that time had a total length 334,36 metres, with 15 arches, the central 9 of which spanning 19,22 m each. It failed in 1971. Note the extremely wide alluvial area full of sand and gravel.

REVIEWER In relation to the other analysed mechanisms that could explain in part the changes in river sediment dynamics and delivery to the coast (section 4), I have some other relevant comments: Land uses and urbanization: as mentioned in the text the change in forest cover is modest, I do not think it can be claimed as the main reason for the sediment deficit in the delta, though it may have some effect (see Ibáñez et al. 2019 and Nienhuis et al. 2020). Besides analysing the changes in land use, is there any possibility to estimate the relative contribution of this phenomenon to the sediment deficit? (the same question applies to the other drivers of change in sediment dynamics in the river).

AUTHORS: The effect of changes in land use are rather connected to the wash load component of the sediment transport, which was not the purpose of the paper (it was bed load instead). We could not have improved the estimates done in the references mentioned by the reviewer, which are duly incorporated in the new paper.

REVIEWER: Dams (sediment trapping): the authors mention that the percent of sediment retention in the two reservoirs of the upper basin may be proportional to the percent surface area that they close. However, it is well known that most of the erosion worldwide comes from the upper parts of the river basins. See for instance Wilkinson & McElroy (2007): Consideration of the variation in large river sediment loads and the geomorphology of respective river basin catchments suggests that natural erosion is primarily confined to drainage headwaters; âĹij83% of the global river sediment flux is derived from the highest 10% of Earth's surface. Then one should expect a higher proportion of sediment retention due to the two dams, which would be concentrated in the last decades, after dam construction.

AUTHORS: The reviewer is right. The paragraph about sediment trap in reservoirs is corrected accordingly, with this argument:

Sediment load coming from the regulated basin as wash load will be mostly trapped in the reservoirs, but the wash load component of the sediment yield, having grainsizes in the clay-silt range (up to 62 μm), is not relevant for the coastline evolution, made of fine sand (280 μm). Regarding the load coming from the channels, ultimately trapped in reservoirs, the drainage network density is similar all over the whole basin, but main rivers and tributaries are steeper in the mountainous regulated basins. Thus, the supply of coarse sediment from channels to the reservoirs is probably larger than 16.5% of the same load at the river mouth (Wilkinson and McElroy, 2007). Sediment supply is resumed in §9.

REVIEWER: Dams (hydrological changes): I am not sure it's a good idea to combine the effect of dam regulation with river engineering to estimate changes in sediment delivery to the coast. In any case, it would be important to have at least an estimate of the change in carrying capacity for the whole river, not only the lower basin.

AUTHORS: The combination of dam regulation and river works produced an estimate of the reduction in carrying capacity in the lower Llobregat, as the reviewer says. This was based on careful archival research of historical river cross-sections, bed gradients and so on, which was possible for the very populated lower Llobregat, not anywhere else. However, the same reduction in carrying capacity for the rest of the river is attempted in the discussion just thanks to the new information about the weirs (small dams).

REVIEWER: Climate change (rainfall and runoff): this possible driver of change in sediment delivery to the coast has been neglected and could be significant. Sand transport capacity is mostly driven by river flow, so changes in river flow due to changes in rainfall and runoff could play a significant role. This possibility should be analysed (see Xing et al., 2014).

AUTHORS: Climate change has not been neglected, actually, but put aside. We think climate change is essential to predict the future of the river and delta, but the purpose of the paper was to explain the past changes, specially in the main period of analysis 1946-1981 (in the discussion it has been extended back to XIX century).

REVIEWER: Channelization and flood plain alteration (river engineering): again the analysis of the alteration of the river bed and the alluvial valley focuses only in the lower river basin, but is quite clear that most of the river basin is engineered (including small dams and other works). So, what is the global contribution of river engineering to the reduction of sediment delivery to the delta? Please try to make a global estimate if possible.

AUTHORS: The role of river engineering in most of the river is now dealt with in the discussion. It is clear now the paramount role of these weirs (small dams), which sum up almost 400 m of head and many kilometres of influence. The estimate we make now is that 80% of the reduction of sediment delivery to the delta is due to the XIX-century engineering works in the middle reaches (small dams) IN COMBINATION WITH a period of anomalous hydrology in 1830-1870. The remaining 20% is due to the XX century encroachment by infrastructures.

REVIEWER: Sand mining: it is mentioned but it would be interesting to have more quantitative information to know the relevance of this activity on the sand deficit to the delta.

AUTHORS: Although there are some data about mining, it is not clear to what extent these extractions participate in the bed load dynamics, provided that most of them are located in the floodplains.

REVIEWER: Other relevant comments regarding beach retreat (sect ion 3): It would be interesting to add an extra graph or table to assess the evolution of the coastal erosion in the delta all over the study period, for instance in the river mouth, in order to see if there is any trend along time and also try to see if this trends match with the assessed trends in sediment delivery to the coast.

AUTHORS: This is done in table 8, by doing our best with the data. For the river mouth specifically, the graph in fig.3 is what the reviewer is asking for. Note that the comparison between the delta and the sediment delivery is restricted to long periods of roughly one decade, because of the calendar of aerial photographs at those times.

REVIEWER: Sediment dynamics in the delta: "The reach is a sedimentary unit throughout the whole period 1891-1981" (lines 60-61). This is not strictly correct, depends on the interpretation of the sentence. Figure 3 shows two different sedimentary units "erosion-accretion" (quite typical in many deltas). This is likely explained by the existence of an old river mouth around Km 10. So it is a sedimentary unit composed by two sub-units.

AUTHORS: The reviewer is right. The text is changed accordingly.

Limits of the Llobregat Delta and sand losses Southwards: "An oval contour slightly protruding into the sea, geographically speaking the delta, can be assigned to the length between x=15 and x=24 km, being the river mouth at x= 21 km" (lines 73-74). "The calculation yields a deficit of 57.000 m3/yr in the delta (x= 15-24 km) and a surplus of 29.000 m3/yr in the beaches west of it (X= 0-15 km)" (lines 93-94). The two sentences should be modified, since the delta is the whole stretch from km 0 to km 24. All deltas have sections with erosion and the corresponding sections with accretion due to the eroding stretch located "upstream" (in relation to the long-shore transport).

AUTHORS: The reviewer is right, also. The text is changed accordingly.

REVIEWER: "The negative balance (loss of sand) can be explained by the partially open western boundary (at x=0)" (lines 101-102). I am no sure that this is the correct explanation. Is there information showing that this volume of sand leaving the delta (quite a lot) is accumulating nearby? Could be the case that there are errors in the calculation of the sediment budget?

AUTHORS: The error in the budget, computed on the grounds of aerial photographs and the USGS procedure, must be small, not more than the accuracy of aerial photographs. We could not find information showing this loss of sand, not even in the publications by well-known CIIRC research centre (referred in the paper).

REVIEWER: Last but not least I recommend to change the structure and title of the manuscript. I suggest something like: “Changes in coarse sediment delivery to the coast during the last century in the Llobregat River: causes and consequences”.

AUTHORS: We remained attached to our title. We think that “What controls” stands for “Changes in” in the reviewer’s alternative title, ídem “yield” for “delivery”, “to a delta” for “to the coast”. The time reference “during the last century” in the alternative is misleading in our view, because the centre of attention is only 1946-1981 and secondly because we have had to look back to 1816 (date of the starting of factory construction), that is to say to TWO centuries. But a title “...to the coast during the last TWO centuries. . .” would also be misleading, in our view.

REVIEWER: In terms of structure I would simplify it and present data in a more integrated way, including a table summarizing the estimated contribution of each component to the changes in sediment delivery and what are the data gaps necessary to get a better estimate.

AUTHORS: The table summarizing the contribution of each component is well beyond our knowledge and abilities. However, some 80% share by the old engineering works in the middle river, and the remaining 20% by the new encroachment of the lower river, was obtained and is highlighted in the conclusion section.

More specifically, this argument goes this way:

The computed annual river yield in 1946-1981 from $\approx 16\times103$ to $\approx 10\times103$ m3/yr is found to be a substantial factor for the delta evolution. It is of the same order of magnitude but lower than the delta balance (âĂŢ28×103 m3/yr). Its variation of ≈âĂŢ6×103 m3/yr between 1956 to 1981 due to the river encroachment by infrastructures, which is our main research objective, is less substantial, but it still accounts for ≈ 20% of the balance. The role of the regulation by dams, ≈ âĂŢ3.5×103 m3/yr, accounts for some 12% of the balance. It must be recalled that the computation is based upon normal flows and annuals floods, not including large floods, whereas the delta evolution (§2) encompasses all phenomena.

REVIEWER: I recommend major changes References Ibáñez, C., Alcaraz, C., Caiola, N., Prado, P., Trobajo, R., Benito, X., ... & Syvitski, J. P. M. (2019). Basin-scale land use impacts on world deltas: Human vs natural forcings. Global and planetary change, 173, 24-32. Nienhuis, J. H., Ashton, A. D., Edmonds, D. A., Hoitink, A. J. F., Kettner, A. J., Rowland, J. C., & Törnqvist, T. E. (2020). Global-scale human impact on delta morphology has led to net land area gain. Nature, 577(7791), 514-518. Wilkinson, B. H., & McElroy, B. J. (2007). The impact of humans on continental erosion and sedimentation. Geological Society of America Bulletin, 119(1-2), 140-156. Xing, F., Kettner, A. J., Ashton, A., Giosan, L., Ibáñez, C., & Kaplan, J. O. (2014). Fluvial response to climate variations and anthropogenic perturbations for the Ebro River, Spain in the last 4000 years. Science of the total environment, 473, 20-31.

AUTHORS: Most the theses references have been mentioned/discussed in the text and added to the reference list. More specifically, these are:

Alayo, J.C. Water and Energy. Hydropower in the Catalan rivers (in Catalan), Pagès ed., Barcelona, 936pp, 2017.

Barriendos, M., Rodrigo, F.S. Study of historical flood events on Spanish rivers using documentary data. Hydrological Sciences Journal, 51(5), 765-783, 2006.

Barriendos, M., Gil-Guirado, S., Pino, D., Tuset, J., Pérez-Morales, A., Alberola, A., Costa, J., Balasch, J.C., Castelltort, X., Mazón, J., Ruiz-Bellet, J.Ll. Climatic and social factors behind the Spanish Mediterranean flood event chronologies from documentary sources (14th-20th centuries). Global and Planetary Change 182, 102997, 2019.

Ibáñez, C., Alcaraz, C., Caiola, N., Prado, P., Trobajo, R., Benito, X., Day, J.W., Reyes, E., Syvitski, J. P. M. Basin-scale land use impacts on world deltas: Human vs natural forcings. Global and planetary change, 173, 24-32, 2019.

Llasat, M.C., Barriendos, M., Barrera, A., Rigo, T. Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documen-

tary sources and old instrumental records. J. of Hydrology 313, 32-27, 2005.

Marcos Valiente, O. Recent changes in the Llobregat delta coastline (in Catalan). I.E.C., 1995.

Marquès, M. A. The Quaternary of the Llobregat delta (in Catalan). Inst. d'Estudis Catalans. 208 pp, Barcelona, 1984.

Paladella, F., Faura Sans, M. Experiences about the Llobregat delta progradation. (in Catalan). Arxius de l'Escola Superior d'Agricultura", 1935. https://upcommons.upc.edu/handle/2099/11137.

Wilkinson, B. H., McElroy, B. J. The impact of humans on continental erosion and sedimentation. Geological Society of America Bulletin, 119(1-2), 140-156, 2007.

Xing, F., Kettner, A. J., Ashton, A., Giosan, L., Ibáñez, C., Kaplan, J. O. Fluvial response to climate variations and anthropogenic perturbations for the Ebro River, Spain in the last 4000 years. Science of the total environment, 473, 20-31, 2014.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2020-72, 2020.

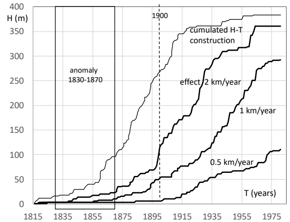

Fig. 1. Cumulative height H (m) versus calendar date for the installation of factories in the middle reaches of the river (data in Alayo, 2017), and its effects at the upper border of the lower Llobregat, und

Fig. 2. Bridge close to town D, shot by well-known French photographer Jean Laurent probably in 1866-1867. The only bridge in lower Llobregat at that time had a total length 334,36 metres, with 15 arches, the